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Report Title

Robust Multivariate Evaluation and Failure Prediction of Inhomogeneous Solids Based on Inverse Analysis

ABSTRACT

During last three years, successful developments and implementations of inverse analyses techniques for advanced materials have been carried out. Furthermore, novel computational approaches were developed to ascertain failure characteristics of inhomogeneous structural systems. These outcomes are described in the published and submitted journal papers. For the identification and evaluations, experimental procedures were developed for nano-, micro-indentations of elastic-plastic graded materials and anisotropic materials. For composites, two separate techniques were developed to identify the embedded delamination and surface damage. Furthermore, hygro-thermal properties of fiber-reinforced materials were determined with an inverse analysis technique. Most of these procedures were conducted with real experiments using instrumented indenters, accelerated weather chambers, loading machines, etc. In terms of developing a new computational tool to understand the mechanics of complex material/structural systems, dynamic crack propagation in functionally graded materials was simulated. Subsequently the method was extended to simulate so-call foreign object damage (FOD). FOD is a main concern in aerospace and power generation industries. In this analysis, an impact of single particle onto heterogeneous material was considered. In addition, 3D modeling of fibrous materials has been initiated to study the deformation and failure of fibrous materials.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

P. Vaddadi, T. Nakamura and R. P. Singh (2005), 'Identification of Hygrothermal Properties in Fiber Reinforced Composites with Inverse Analysis Approach', accepted to appear on Journal of Composite Materials.
T. Nakamura, R. P. Singh and P. Vaddadi (2005), 'Effects of Environmental Degradation on Flexural Failure Strength of Fiber Reinforced Composites' Journal of Experimental Mechanics.
N. Ramanujam, T. Nakamura, M. Urago (2005), 'Identification of Embedded Interlaminar Flaw using Inverse Analysis', International Journal of Fracture, 132, 153-173.
Y. Gu and T. Nakamura (2004), 'Interfacial Delamination and Fatigue Life Estimation of 3D Solder Bumps in Flip-Chip Packages', Microelectronics Reliability, 44(3), 471-483.
Z. Wang and T. Nakamura, (2004), 'Simulations of Crack Propagation in Elastic-Plastic Graded Materials', Mechanics of Materials, 36/37, 601-622.
T. Nakamura and Z. Wang (2004), 'Inverse Analysis to Estimate Critical Crack Propagation Parameters for Elastic-Plastic and Graded Materials,' Key Engineering Materials, 261, 117-122.
T. Nakamura and Z. Wang (2004), 'Inverse Analysis to Estimate Critical Crack Propagation Parameters for Elastic-Plastic and Graded Materials,' Key Engineering Materials, 261, 117-122.
Z. Wang, A. Kulkani, S. Deshpande, T. Nakamura, H. Herman, (2003), 'Effects of Embedded Pores and Interfaces on Plasma Sprayed Coatings', Acta materialia, 51, 5319-5334.
Y. Gu, T. Nakamura, L. Prchlik, S. Sampath, and J. Wallace (2003), 'Micro-Indentation and Inverse Analysis to Characterize Elastic-Plastic Graded Materials', Mater. Sci. and Engineering, 345, 223-233.
Y. Gu, T. Nakamura, L. Prchlik, S. Sampath, and J. Wallace (2002), 'Indentation and Inverse Analysis to Characterize Elastic-Plastic Graded Materials', Materials Science and Engineering, 345, 223 – 233.

Number of Papers published in peer-reviewed journals: 10.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

T. Nakamura, R.P. Singh, P. Vaddadi and N. Ramanujam (2005), 'Effects of Environmental Degradation on Flexural Failure Strength of Fiber Reinforced Composites,' Proceedings of Society of Experimental Mechanics.
T. Nakamura and Y. Gu (2003), 'Measurements of elastic-plastic anisotropic properties of thermally sprayed coatings using nano-indenters and inverse analysis technique,' Proceedings of International Thermal Spray Conference.
T. Nakamura and Z. Wang (2003), 'Dynamic Failure Behavior of Elastic-Plastic Graded Materials,' Proceedings of 9th International Conference on the Mechanical Behavior of Materials, Geneva, May 2003.

Number of Papers published in non peer-reviewed journals: 3.00

(c) Papers presented at meetings, but not published in conference proceedings (N/A for none)

‘Inverse Analysis to Determine Properties of Anisotropic Thin Films and Coatings’, Symposium on Physics and Mechanics of Advanced Materials, IMRE, Singapore, January 2006.
‘Nonlinear Properties in Plasma Sprayed Coatings and Relation to Process/Materials’, Consortium on Thermal Spray Technology, Stony Brook, December 2005.
‘Effects of Fatigue and Degradation on Residual Strength of Composite Laminates’, ASME 2005 IMECE, Orlando, November 2005.
‘Novel Approach to Extract Stress-Stress Relations of Plasma Sprayed YSZ Coatings’, Consortium on Thermal Spray Technology, Stony Brook, December 2004.
‘Simulations of Multiple Cracking Phenomena in Inhomogeneous Materials under Dynamic Impact’, ASME 2004 IMECE, Anaheim, November 2004.
‘Effects of Pores and Interfaces in Plasma Sprayed PSZ Coatings’, Joint US-Japan Workshop on Materials and Coatings for High Temperature Environment, Stony Brook, October 2004.
‘Measurements of elastic-plastic anisotropic properties of thermally sprayed coatings using nano-indenters and inverse analysis technique’, International Thermal Spray Conference and Exposition, Osaka, May 2004.
‘Determination of Anisotropic Properties using Nano/Micro-Indentation and Inverse Technique,’ ASME 2003 IMECE, Washington DC, November 2003.
‘Interfacial Delamination and Fatigue Life Estimation of 3D Solder Bumps in Flip-Chip Packages,’ (Invited), Symposium on Electronic Devices by Japanese Society of Mechanical Engineers, Tokyo, June 2003.
‘Effects of Embedded Pores and Interfaces on Plasma Sprayed Coatings: Thermal Spray Research at State University of New York at Stony Brook,’ (invited) 52nd Conference of Japan Society of Materials, Tokyo, May 2003.
‘Failure and Damage Evaluations of Inhomogeneous Materials Based on Inverse Analysis Techniques,’ 16th U.S. Army Symposium on Solid Mechanics, Charleston, SC, May 2003.
‘Inverse Analysis and Instrumented Indentation to Determine FGM Parameters,’ ASME 2002 IMECE, New Orleans, November 2002.

Number of Papers not Published: 12.00

(d) Manuscripts

N. Ramanujam and T. Nakamura (2006), ‘Estimation of Surface Damage Distribution in Composite Panels via Inverse Analysis’, submitted to Journal of Composite Materials (in April 2006).
T. Nakamura and Y. Gu (2005), ‘Identification of Elastic-Plastic Anisotropic Parameters using Instrumented Indentation and Inverse Analysis’, submitted to Mechanics of Materials.
P. Vaddadi, T. Nakamura and R. P. Singh (2004), ‘Identification of Hygrothermal Properties in Fiber Reinforced Composites with Inverse Analysis Approach’, submitted to Journal of the Mechanics and Physics of Solids.
N. Ramanujam and T. Nakamura (2004), ‘Inverse Analysis to Estimate Surface Damage Distribution of Thin Panels’, submitted to International Journal of Solids and Structures.
P. Vaddadi, B. G. Kumar, R. P. Singh and T. Nakamura (2004), ‘Residual Strength of Composites subjected to Multi-Property Degradation Mechanisms’, submitted to Acta materialia.

Number of Manuscripts: 5.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED	
Narayanan Ramanujam	90.00	No
Yu Gu	30.00	No
Zhiqiang Wang	25.00	No
FTE Equivalent:	**145.00**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Toshio Nakamura	8.25	No
FTE Equivalent:	**8.25**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Personnel receiving masters degrees

NAME	
Narayanan Ramajunam	No
Total Number:	**1**

Names of personnel receiving PHDs

NAME	
Yu Gu	No
Zhiqiang Wang	No
Total Number:	**2**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Summary of Projects under 44232-EG

At the initial phase, a new inverse analysis technique was utilized to detect damage of composite panel. Small strength change due to damage is detected by strain gages and this information was used as input to estimate the variation of surface degradation on composite panel as shown in Fig. 1.

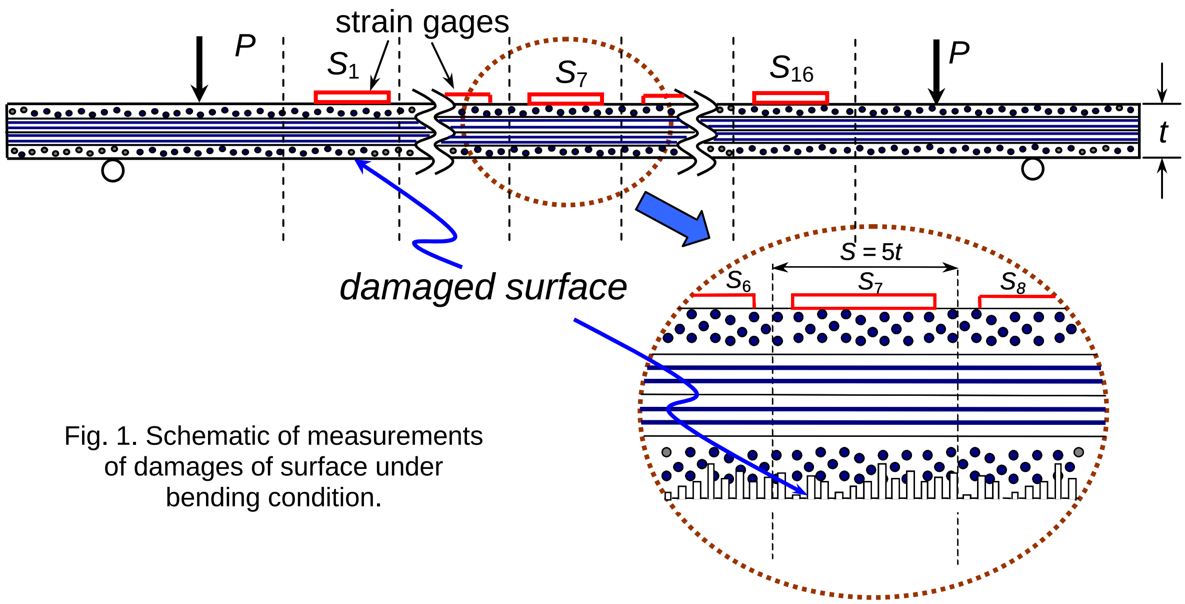

Fig. 1. Schematic of measurements of damages of surface under bending condition.

Here the relationship between the damage amount and the degradation was established with the *singular value composition method* and the estimates were made with the *multivariate Newton-Raphson method* as the procedure is shown in Fig. 2. The simulated results in verification study confirmed the high accuracy of estimates based on this procedure, as shown in Fig. 3. A similar approach can be applied to other types of materials and conditions to determine unknown damage distributions.

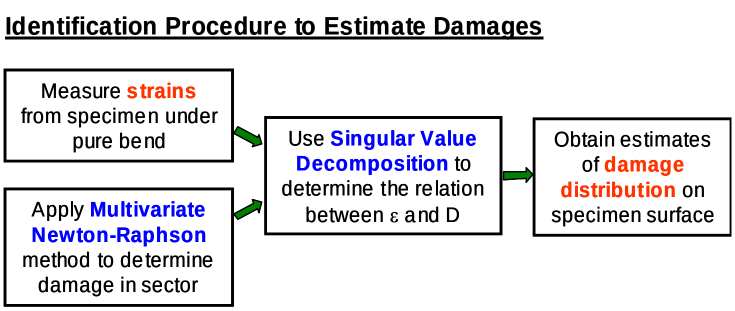

Fig. 2. Schematic of identification process based on inverse analysis.

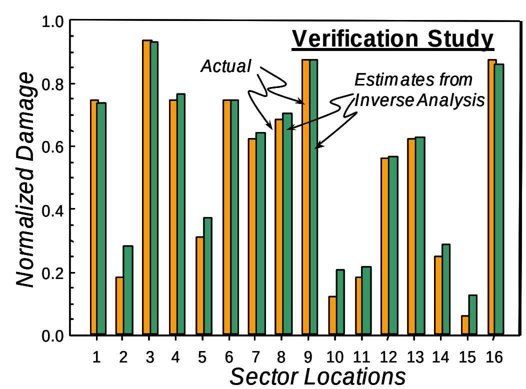

Fig. 3. Simulated results showing good agreements between the estimates and actual damages.

For computational procedure development, a significant advance in the simulations of dynamic crack propagation within functionally graded materials (FGMs) was made. The analysis is more robust and able to carry out more stable computations. After successful simulations of dynamic crack propagation, a focus was shifted to investigate the determination of critical fracture parameters from available testing methodologies. They are the separation energy and the maximum peak stress needed to cause growth advance. Without these parameters, no meaningful results can be obtained with any computational means. This approach uses the *Kalman filter* and indirect measurements as illustrated in Fig. 4.

Fig. 4. Schematic of inverse analysis to determine failure

Our verification study using a double-cantilever-beam specimen proved the robustness of this method as shown in the convergence map of estimation in Fig. 5. In addition, preliminary fracture tests were conducted on FGMs. An improved testing is planed to obtain useful data from this test.

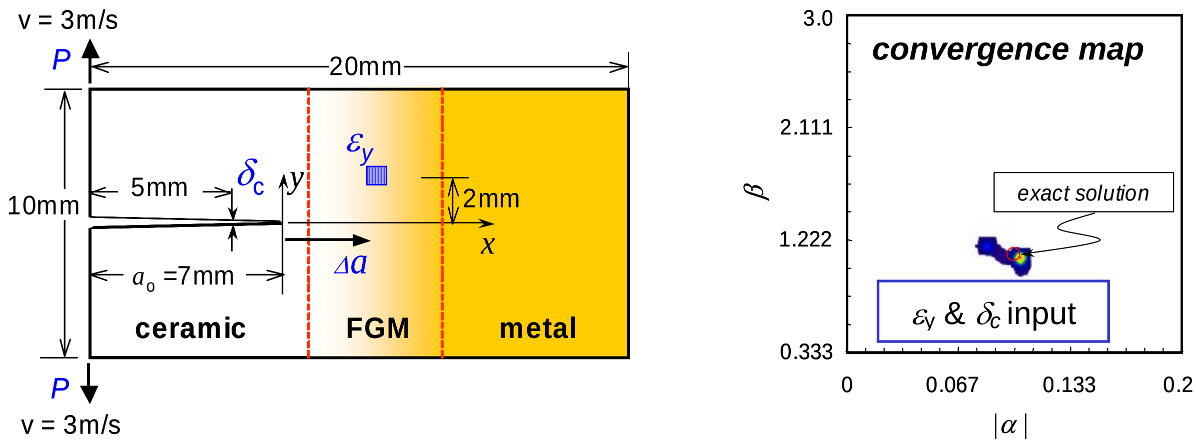

Fig. 5. Schematic of specimen tested for inverse analysis and the resulting convergence map based on two input measurements. They converged to the exact solution.

For in the simulation of impact problem, where high velocity strikes the FGM protective coating as shown in Fig. 6. Here two different grading of ceramic and metal are simulated.

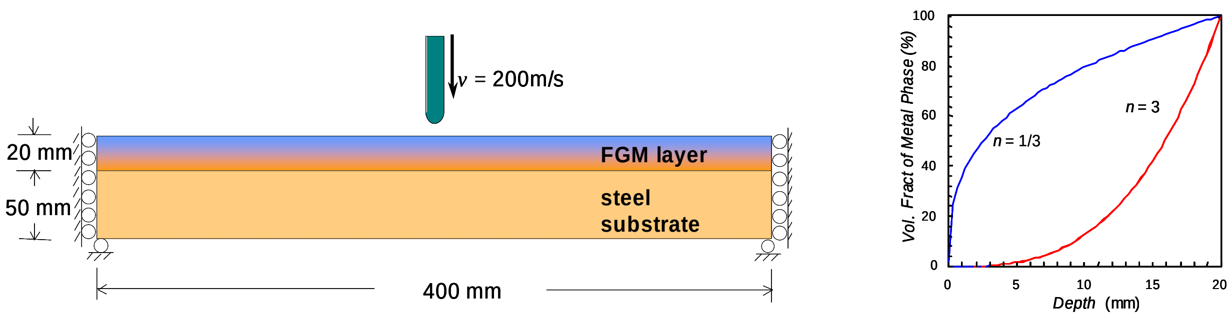

Fig. 6. Schematic of impact onto graded layer and two ceramic-metal different grading profiles through thickness.

The analysis show, the cracking pattern and energy dissipation are influenced by various grading of phases through thickness as shown in Fig. 7. Here n = 1/3 has greater metal phase and the cracking tends to spread out rather than going down. Furthermore, this profile dissipated greater amount of energy as the impact goes through. This information can be used to design layers to maximize energy dissipation within armors.

In addition, under a partial funding of ARO, stress and failure of electronic packaging work was conducted (Gu and Nakamura, 2002). As more I/O connections are required in new generation of semiconductors, flip-chip geometry is becoming more popular. The analysis quantified the three-dimensional effects on local fracture behaviors under thermal load and to estimate thermal fatigue life of solder bumps.

Investigations on the inverse analysis with indentations was utilized to detect anisotropic properties of thin films and coatings. Owning to their fabrication processes, they often exhibit anisotropic responses but their property determinations are usually difficult due to their small scale. Here simple experimental measurements from depth-sensing nano- and micro indentations and the Kalman filter are used to obtain the key anisotropic parameters. The parameters allow complete descriptions of stress-strain relations of anisotropic materials. The nano-indenter was acquired through a separate ARO equipment grant (DAAD 19-01-1-0709). The critical feature of this work is that it utilizes two separate indentations with different heads as shown in Fig. 8.

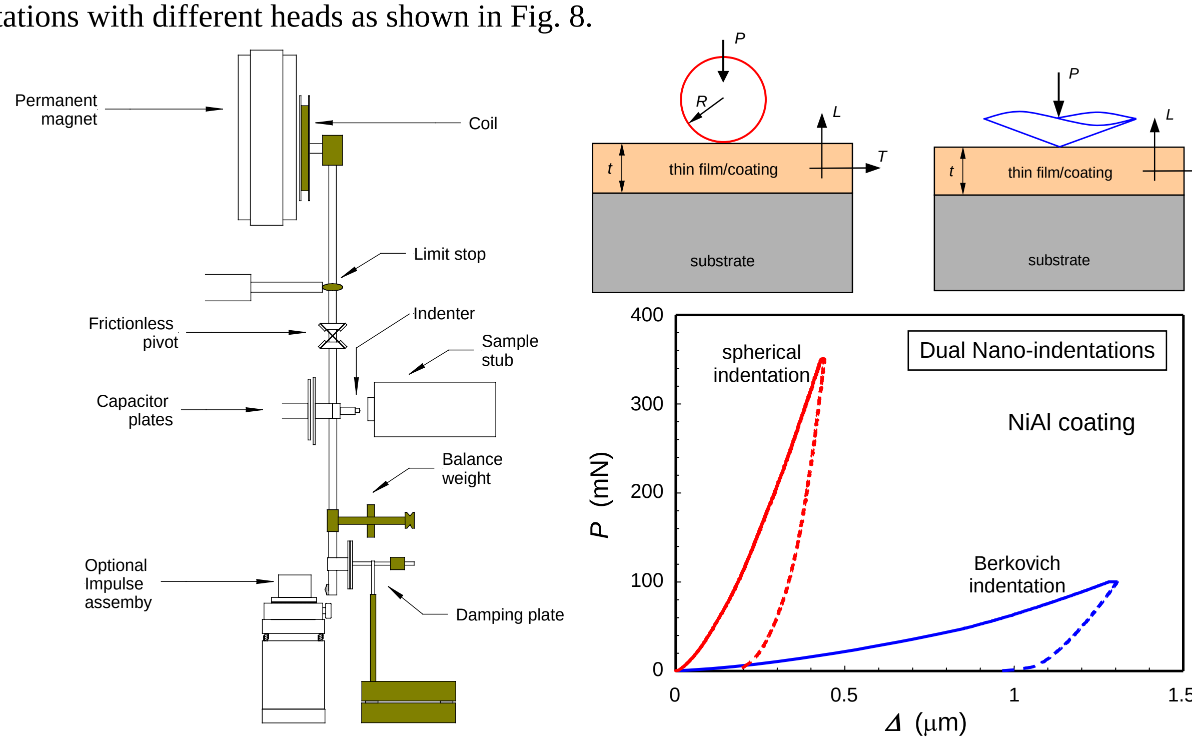

Fig. 8. Schematics of nano-indenter and two different indenter heads, spherical and Berkovich. The indented load-displacement records of NiAl coating are shown.

The dual-indentation system offers simple but additional information necessary to estimate the complex unknown property. In the experiment, plasma sprayed NiAl coating was examined. Using the load-displacement record, shown in Fig. 8, as the input, the inverse analysis was carried out to obtain the best estimates of properties. The convergence maps are generated to estimate the likely values as shown in Fig. 9. Once the best estimates are extracted, the stress-strain relations of the NiAl coating can be constructed as shown in Fig. 10. Prior to the

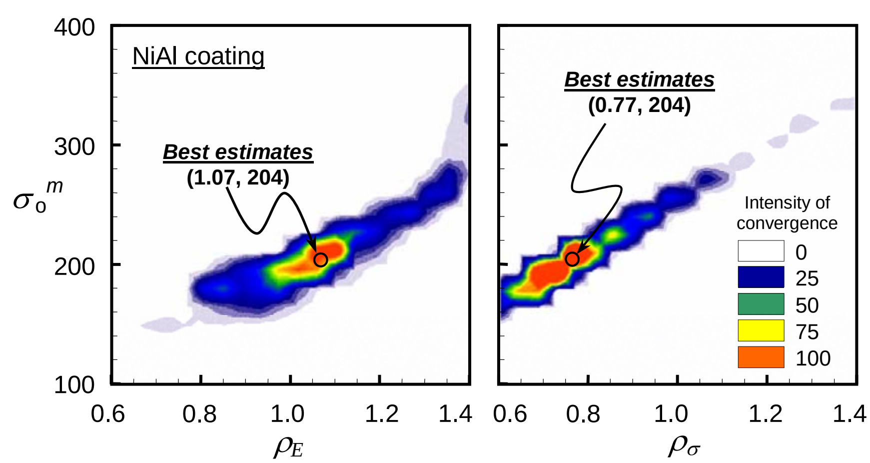

Fig. 9. Convergence maps generated after Kalman filter analysis. They show likely values of three known material properties.

actual testing, detailed verification studies were performed to evaluate the present procedure's effectiveness and accuracy. Similar analyses were also carried out with the micro-indenter. The comparison of the results can be used to evaluate the size effect of the specimen.

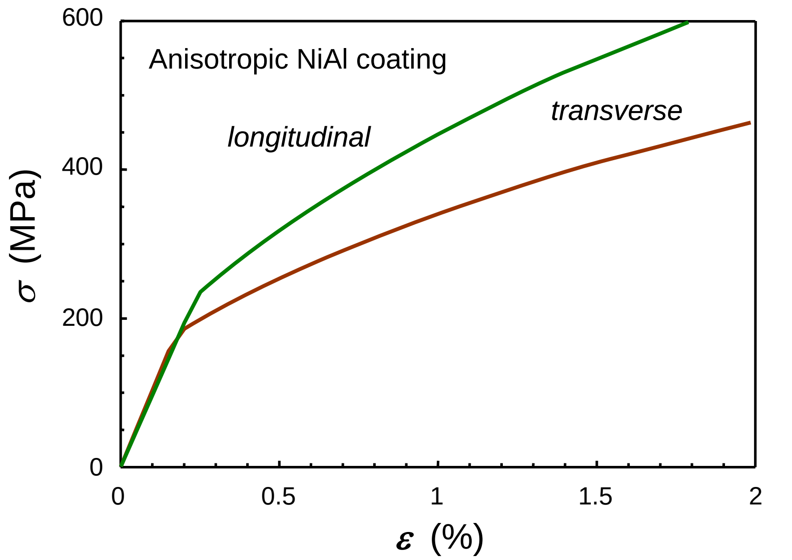

Fig. 10. Transversely isotropic stress-strain relations estimated by the inverse analysis. The longitudinal direction shows stiffer response.

In addition, simulation of impact was improved by controlling stability condition in the numerical analysis. The cracking and fragmentation as well as stress contours underneath are shown in Fig. 11. The paper was accepted for publication on this work (Wang and Nakamura, 2004).

Also the estimation of damage/degradation of composite panel based on an inverse analysis was completed and submitted for publication (Ramanujam and Nakamura, 2004). The aim of this work is development of a method that requires less experimental efforts than those of conventional techniques with an aid of intelligent post-processing scheme. Here the damage field is assumed to occur due to environmental conditions and their distributions are indirectly detected by strain measurements. This information was used in an inverse analysis to estimate the variation of surface degradation.

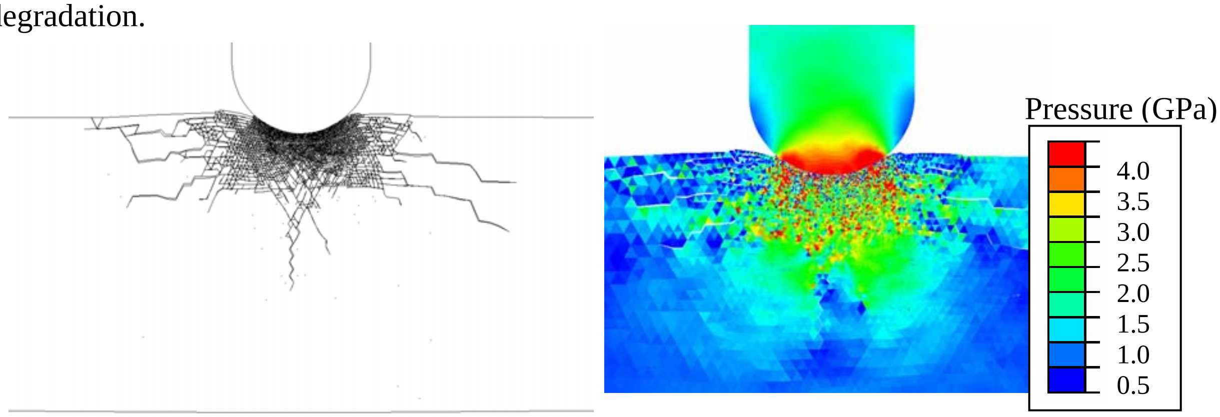

Fig. 11. Multiple cracking and fragmentation after impact and stress contours underneath the impact.

In addition, under a partial funding of ARO, stress and failure of electronic packaging work was completed and its 3D paper was published (Gu and Nakamura, 2004). In this work, flip-chip geometry was considered and the investigation quantified the three-dimensional effects on local fracture behaviors under thermal load.

Identification of embedded delamination in composite laminate based on an inverse analysis is completed In the second study, geometrical parameters of embedded delamination in composite laminate, as shown in Fig. 12, were estimated. Here the size and location of the interlaminar delamination were estimated from strain measurements supplied to the downhill simplex method. The procedure first constructs approximate functions relating delamination parameters to available measurement parameters with interpolation functions. Then, the multi-dimensional minimization technique is adopted to search for the best estimates of unknown parameters corresponding to the lowest error objective function. In order to increase the accuracy of estimates, the deflection at load point was also included as the measurement inputs. Additional improvements were observed when those measurements under multiple loading conditions are included. A detailed error sensitivity analysis is also carried out to confirm the method's robustness as shown in Fig. 13. Such an analysis is useful since errors/noises are common in actual tests. The paper (Narayanan, Nakamura and Urago, 2004) was submitted for publication. To explore other possible techniques, a genetic algorithm was also tested to identify the unknowns.

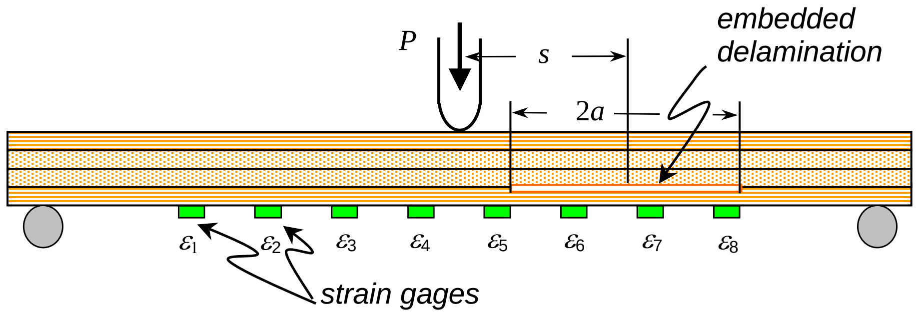

Fig. 12. Schematic of 4 ply $[0/90]_s$ laminate containing an embedded interlaminar delamination subjected to three-point-bend.

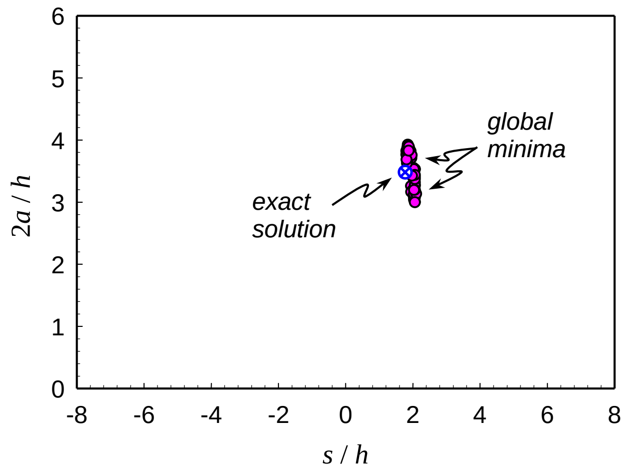

Fig. 13. Global minima in the error sensitivity analysis with 50 separate cases with different random errors added to measurements.

The inverse analysis was also utilized for determination of critical hygrothermal properties of fiber-reinforced epoxy matrix composites, which is being considered for next-generation rotor blade application. These parameters are essential in quantifying degradation of composites (shown in Fig. 14) n humid and high temperature environment. The unknown parameters were the diffusivity, maximum moisture content, and coefficients of thermal and moisture expansion under various environmental exposure conditions. In the procedure, an inverse analysis technique in conjunction with a detail computational model was utilized to process records of weight gain and expansions. The strains were measured with fiber optic sensors, which are suitable in harsh environments. The estimates were obtained from the intensity of convergence plots generated by the Kalman filter as shown in Fig. 15.

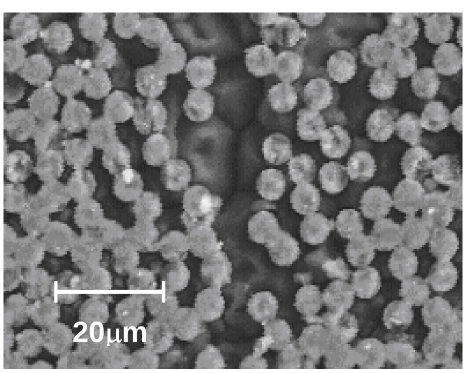

Fig.14. SEM showing degraded composites under moisture absorption and ultra-violet radiation. Matrix erosion and cracking can be observed.

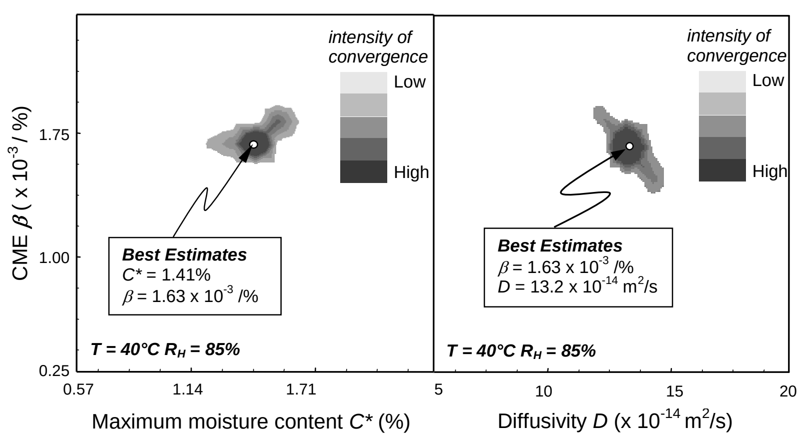

Fig. 15. Intensity of convergence plots obtained from inverse analysis reflecting best estimates for three moisture absorption parameters.

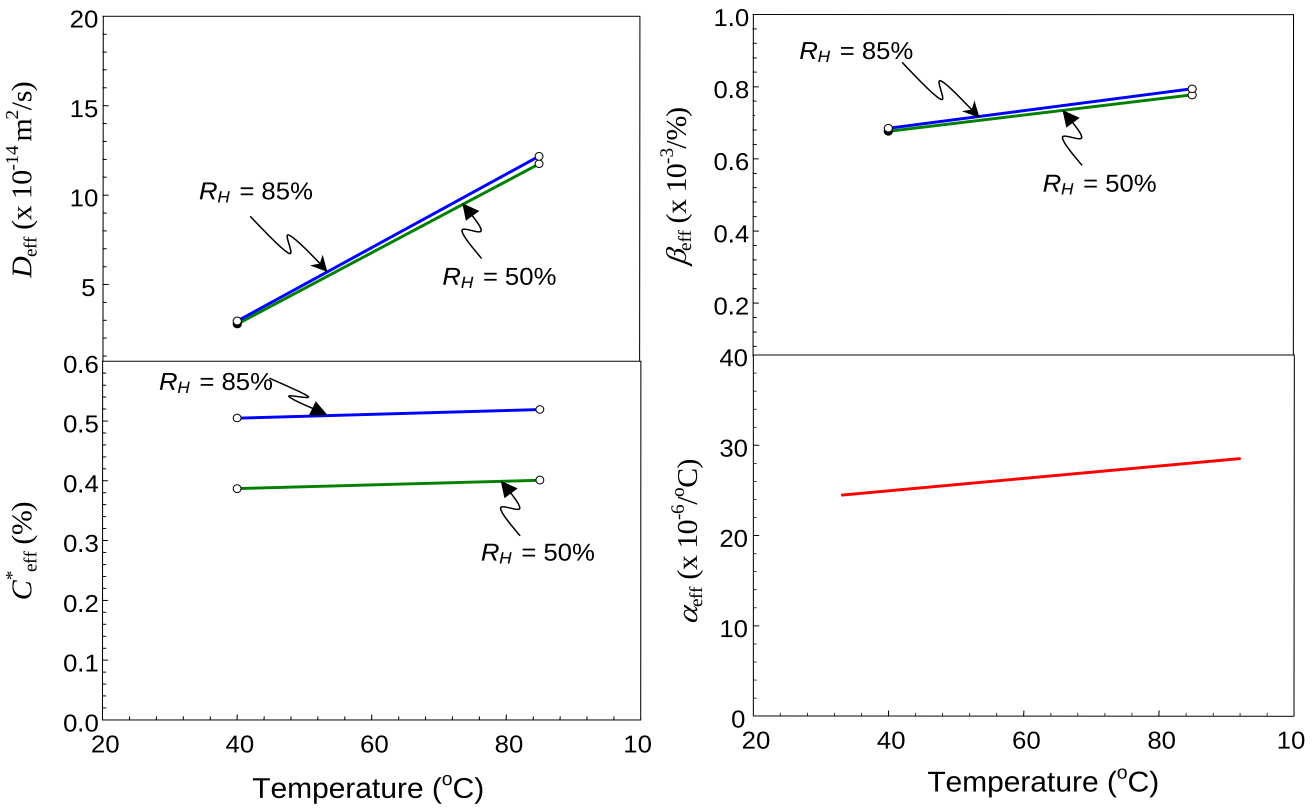

Fig. 16.Temperature and relative humidity dependences of critical hygrothermal parameters of fiber-reinforced composites.

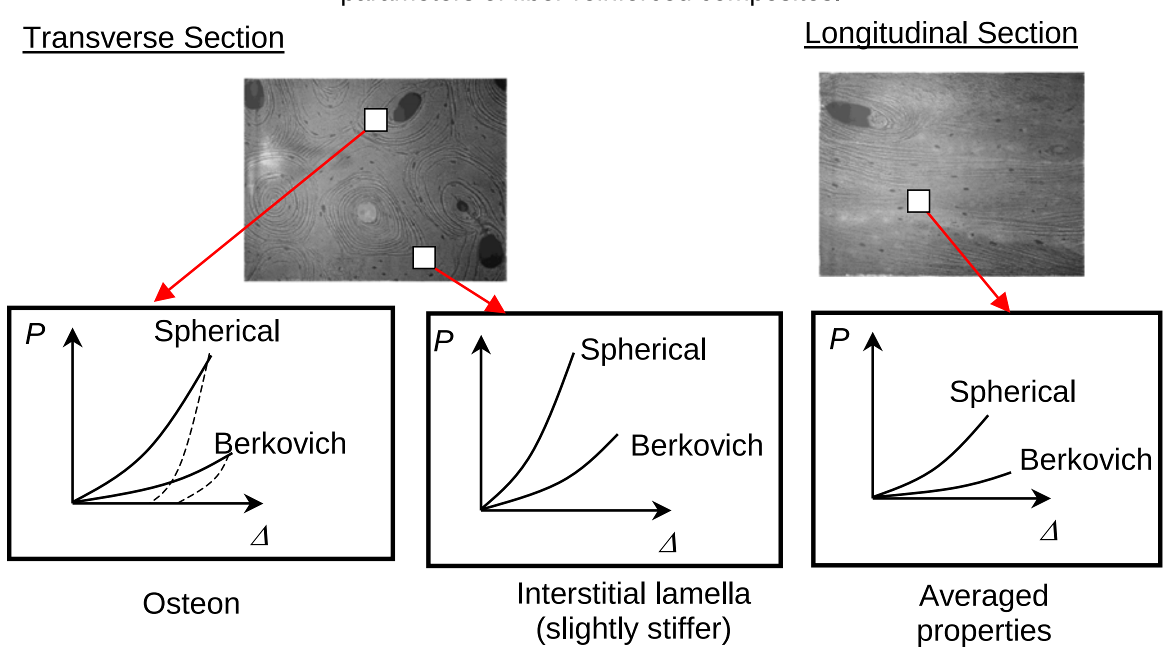

Fig. 17. Micro-indentation are made on both transverse and longitudinal sections of bone. To gain more information, two distinctly different indenter heads are to be used.

The analysis found the diffusivity to be a strong function of temperature while the maximum moisture content to be a strong function of relative humidity as shown in Fig. 16. For the expansion rates, moisture induced strains as well as thermal strains exhibited slight dependence on temperature. Our analysis also uncovered the source of scattering expansion measurements during heating and moisture absorption processes. Apparently, the residual stresses embedded during the composite's fabrication caused the unsteady expansions. As the stresses were relieved by repeated heat cycles, smoother expansion measurements were observed. In related work, to understand the effects of multiple degradation mechanisms on composite was also carried out. Here environmentally degraded as well as mechanically fatigued specimens were tested to quantify the their residual strengths. Here an empirical formula was established to clarify effect of mechanism (Vaddadi, et al., 20044).

Additional work is underway to extend the inverse analysis to biomaterials. Here possible procedures to measure mechanical properties of various phases in bone are explored. Since many biomaterials are inherently anisotropic, a more complex procedure is needed to characterize their behavior. For example, in cortical bones, two major phases are secondary osteon and interstitial lamella. Both of them run along the longitudinal direction. One possible test method is illustrated in Fig. 17. The scheme is supply the measured records to an appropriate inverse analysis and process the data to extract the best estimates of unknown parameters. In this study, the size-scale is also a critical issue. It is elucidate how the responses of individual phases at micro-scale translate to the overall responses of bone at macro-scale.

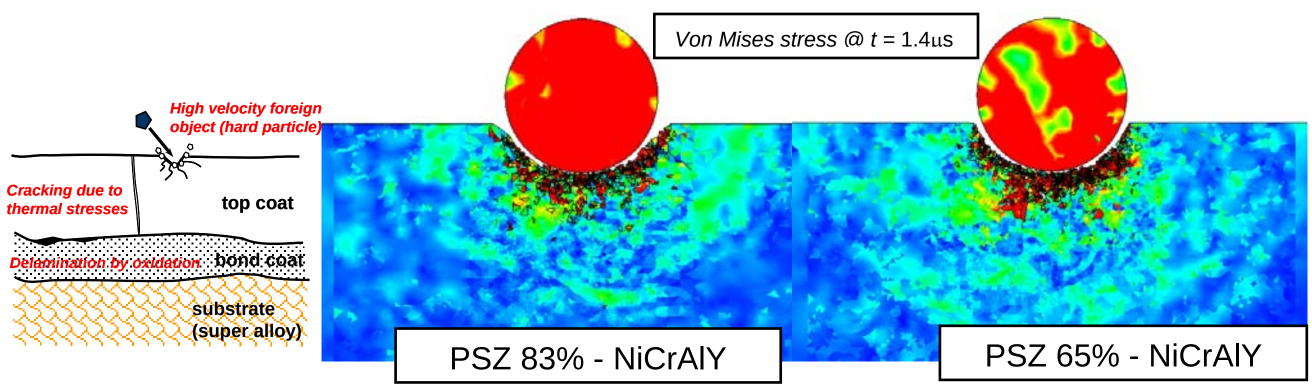

Fig. 18. Simulations of FOD onto heterogeneous materials with brittle (PSZ) and ductile (NiCrAlY) phases.

A novel computational model was utilized to simulate impact damage of coatings/layers. So-call foreign object damage (FOD) is a main concern in aerospace and power generation industries where turbine blades are damaged and abraded with many high-speed particles. As an initial study to quantify the damage caused by FOD, an impact of single particle onto heterogeneous material was considered. Here fragmentations of near surface material were simulated with appropriate fracture criteria. The target material is directly modeled from micrographic image of thermally sprayed coating containing brittle partially stabilized zirconia (PSZ) and ductile NiCrAlY phases. For the fracture condition, three different critical separation energies are assigned for the PSZ, NiCrAlY and their interfaces. As the particle strikes the surface, multiple-cracking occurs and erodes the material. The process continues until the kinetic energy of the impacting particle dissipates into the fracture energy and plastic dissipation of ductile phase, and transfer to the strain and kinetic energies of material. Our results clearly indicate that phase compositions of PSZ and NiCrAlY play an important role in defining the amount of damage caused by the striking particle as shown in Fig. 18. In addition, the effects of homogenization, angled impact, and porous materials were also investigated.

In order to prove the concept of previously proposed process to estimate damage/degradation of composite panel due to environmental degradation and physical damage, actual measurements using so-call strip strain gage (Vishay Measurements, Inc.) were made. The strip gage consists of 10 equally spaced (4mm) strain gages and can be bonded onto any composite surfaces. These gages are used to measure axial strain changes due to presence of surface damage. The measured strains were used in the inverse analysis to extract the distribution of extent of surface damages. In addition, during the establishment of the relationship between the strain and the damage extent, a new approach was introduced. In the previous approach (Ramanujam and Nakamura, 2004), a model functions and the singular value composition method were utilized. However this approach is ineffective when the strain-damage relation cannot be represented by smooth functions. In order to circumvent this problem, B-spline method was adopted in the establishment of strain-damage relation. The B-spline is a powerful approach that is commonly used to represent 3D surfaces in the design field. In the final estimation, the multivariate Newton-Raphson method extracted the damage distribution. The estimated damage obtained through actual measurements show the robustness of this procedure as shown Fig. 19.

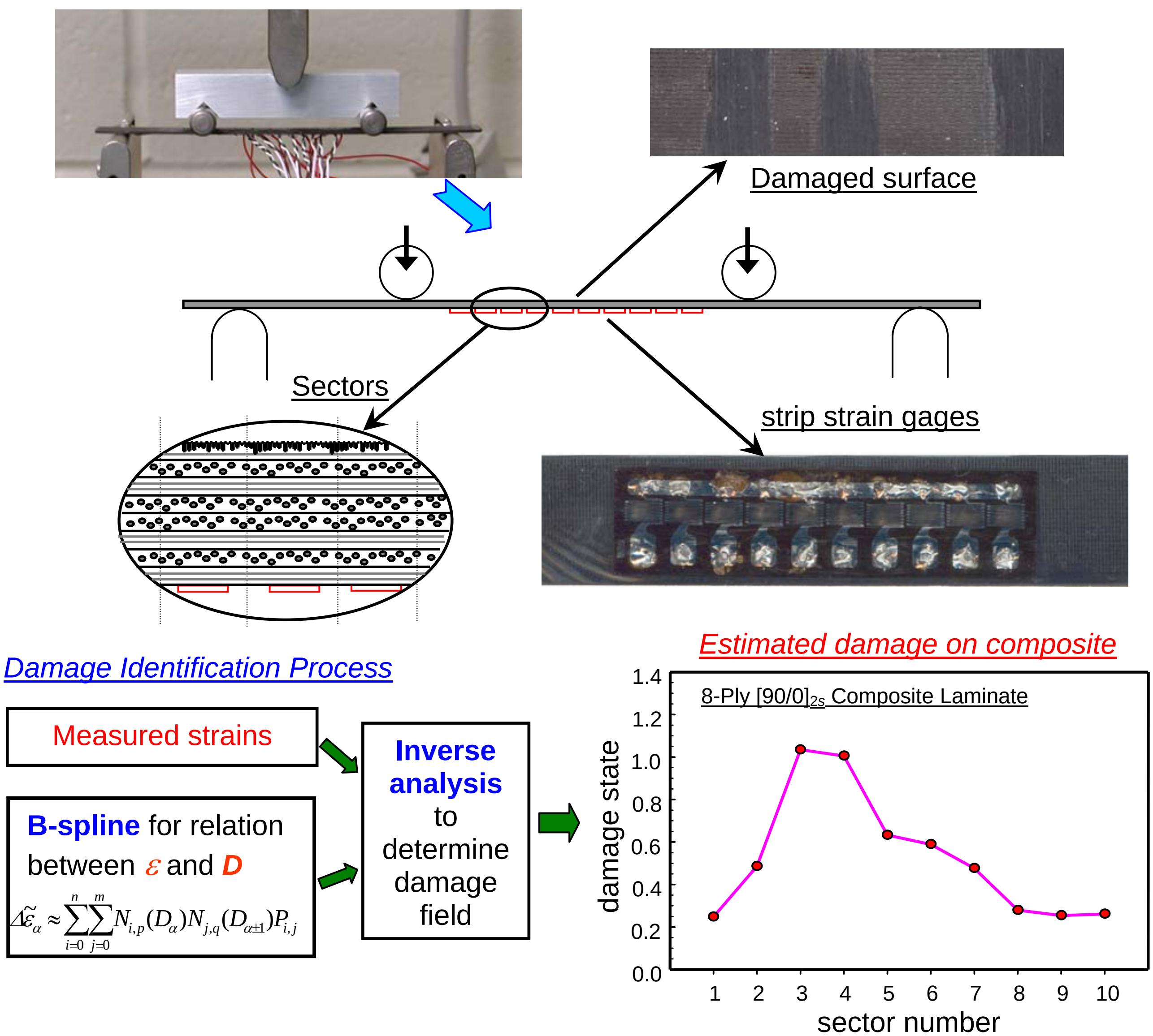

Fig. 19. Experimental set-up to measure surface damage with strip strain gage and inverse analysis.

Third, since many of advanced heterogeneous materials cannot be modeled accurately with 2D geometries, 3D modeling of fibrous materials has been initiated. The application includes fiber-reinforced composites as well as many of bio-materials (bone, wood, etc.). Here long fibers that posses differently properties from matrix are discretely modeled. This model is first utilized in the indentation simulation. In order to maximize the computational resources, homogenized phase of effective properties is added to the model as shown in Fig. 20. The computed results also show the differences between 3D and 2D models, which attest the importance of 3D models.

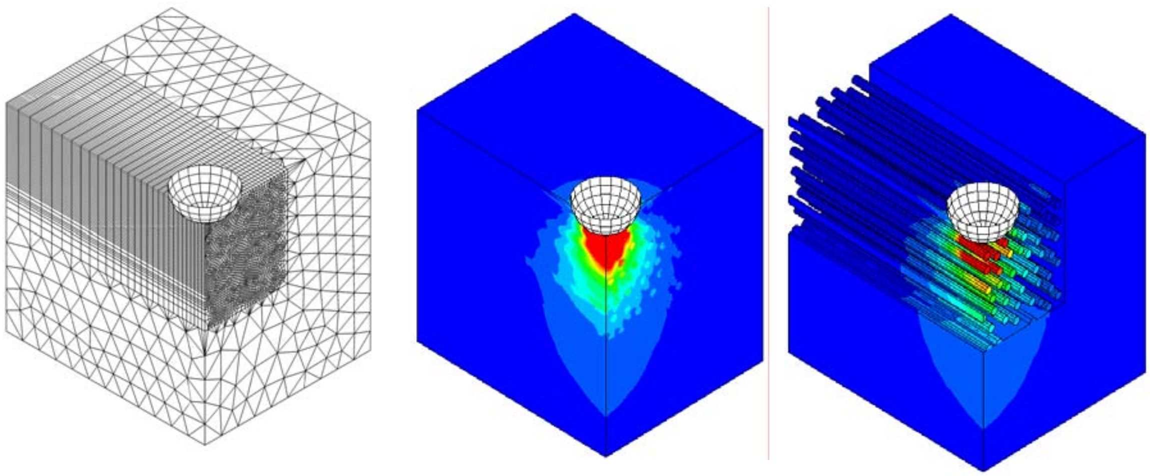

Fig. 20. Construction of 3D mesh for fibrous material and simulated indentations.